

**Autofrettage to Counteract Coefficient of Thermal Expansion Mismatch in Cryogenic
Pressurized Pipes with Metallic Liners**

Ed Wen, Ever Barbero and Philip Tygielski

Abstract

Composite feedlines with metal liners have the potential to reduce weight/cost while providing the same level of permeation resistance and material compatibility of all-metal feedlines carrying cryogenic propellants in spacecraft. The major technical challenges are the large difference in Coefficient of Thermal Expansion between the liner and the composite, and the manufacturing method required to make a very thin liner with the required strength and dimensional tolerance. This study investigates the use of autofrettage (compressive preload) to counteract Coefficient of Thermal Expansion when pre-pressurization procedures cannot be used to solve this problem. Promising materials (aluminum 2219, Inconel 718, nickel, nickel alloy) and manufacturing techniques (chemical milling, electroplating) are evaluated to determine the best liner candidates. Robust, autofrettaged feedlines with a low Coefficient of Thermal Expansion liner (Inconel 718 or nickel alloy) are shown to successfully counteract mismatch at LOX temperature. A new concept, autofrettage by temperature, is introduced for high Coefficient of Thermal Expansion materials (aluminum and pure nickel) where pressure cannot be used to add compressive preload.

Nomenclature

A = area
 E = modulus
 I = moment of inertia
 P = pressure
 R, r = radius
 t = thickness
 T = temperature
 α = coefficient of thermal expansion
 ε = strain
 σ = stress
 ν = Poisson's Ratio

Subscripts

c = composite
 CR = critical for buckling
 m = metal
 T = temperature
 o = due to autofrettage

Introduction

Feedlines carrying pressurized cryogenic propellants, such as liquid oxygen (LOX) and hydrogen (LH2), have long been identified as potential areas for spacecraft weight reduction when used with composite materials. While composite feedlines for LH2 have been demonstrated successfully, composite LOX feedlines are still under development because composites are typically not able to pass the LOX compatibility requirement in NASA-STD-6001. One approach has been to develop epoxies that can pass an alternative standard of compatibility more suited to the specific conditions of the feedline. [1] This approach was used for an all-composite LOX pressure vessel where the flow velocities are relatively low. Because feedlines have higher flow velocities and more direction changes than pressure vessels, the approach of this investigation is to use a thin metallic liner that is compatible with LOX.

Based on NASA Marshall Space Flight Center recommendation, the all-aluminum LOX feedline on the External Tank (ET) of the Space Shuttle were chosen for study (Figure 1). To reduce complexity but be representative, one of the straight sections was chosen and the support sections attaching the feedline to the ET were not incorporated. Additionally, the loads from the

highest loaded straight section (lowest of the four) were used to be conservative. Future study will result in integrating curved and straight sections, both fabricated with autofrettage procedures.

By pre-pressurizing the feedline, the large shrinkage of the metal liner caused by LOX can be controlled so that the liner does not separate from the composite outer casing. Unfortunately this increases operation complexity, such as during emergency shutdown, and was therefore viewed as an unacceptable solution to the CTE mismatch between the liner and composite.

Autofrettage is commonly used to make lightweight composite pressure vessels with internal metal liners. The liner acts as a permeation barrier, preventing material incompatibilities between the composite and stored fluid. By pressurizing (or autofrettaging) the liner beyond its elastic limit, a residual compressive stress remains in the liner when the vessel is at zero pressure, which effectively increases the elastic tensile strain capability of the liner and the maximum pressure allowed in the pressure vessel. In addition to this obvious asset, resistance to fatigue and fracture is improved. In the case of a cryogenic fluid, autofrettage could also be used to counteract shrinkage of the liner, preventing the liner from “pulling away” from the composite wall at cryogenic temperature and zero pressure.

Presently, there is no known case of autofrettage being used for *composite cryogenic feedlines*. Currently, some component manufacturers have considered autofrettage in metal lined *composite cryogenic pressure vessels* but these attempts did not result in production articles. NASA Marshall and JPL are studying metal lined composite cryogenic pressure vessels *that use pre-pressurization as a means to counteract CTE*. It is possible that classified programs have

used autofrettage with composite cryogenic pressure vessels, but this information is not publicly available.

West Virginia University has researched metal liners in composite pressure vessels and more recently, in composite high-pressure pipes for the oil industry. The autofrettage approach was used successfully in a filament wound carbon/fiberglass pipe with steel liner designed for 22.5 ksi. [2] Although this pipe did not carry a cryogenic fluid, it is the first known application of autofrettage in a pipe with flanges.

Thiokol researched and demonstrated a composite LH2 pressure vessel using an aluminum foil liner, but without autofrettage [3]. This liner was fabricated by laying up sections of 0.002" thick aluminum foil onto a sand mandrel. The composite was then filament wound with the Invar 36 polar bosses (end sections) being wound into the case. When cured, the sand mandrel was washed out of the composite case. The tank completed many of the tests before leaking during the long-term LH2 pressure tests.

Carleton Pressure Technology Division is making a high performance pressurized Xenon tank for the Mars Lander project, which is not expected to see cryogenic temperature. It has a 0.005" thick aluminum liner bonded with a film adhesive to the composite case, having approximately an 18-inch outer diameter. To date, this project appears to be fabricating the thinnest metal liner that is autofrettagged.

Lockheed/Martin Corporation tested the first all (unlined) composite LOX pressure vessel for the air launched X-34 re-entry vehicle [1]. Their initial investigation included several coated and lined PMC materials for the LOX tank. Liners materials, such as aluminum foil, Mylar, Kapton and Teflon were not able meet all the established LOX compatibility criteria and the number of cryogenic/mechanical cycles required for a reusable launch vehicle without

microcracking/debonds. Polymers like Mylar, Kapton and Teflon held promise because of their low density, but experienced microcracking at cryogenic temperatures, allowing permeation. Additionally, each batch of material had to be compatibility tested for variations in the manufacturer's processing, i.e. seams and local debonds, etc. Ultimately, Lockheed/Martin decided to use a proprietary toughened modified epoxy PMC system that passed alternative tests using the established approach in NASA-STD-6001 for LOX compatibility. The tests were devised to evaluate the hazards specific to the mission/hardware and the results showed that the liner could be eliminated. It should be noted that Lockheed/Martin is researching the conversion of the Shuttle's LOX feedline systems to all un-lined composite, funded as an Internal Research and Development program.

As early as 1982, [4] discussed autofrettage as one of three methods to counteract the CTE mismatch for an integral cryogenic pressure vessel carrying flight loads. The first method was to use only autofrettage to counteract the CTE mismatch, but the liner was expected to buckle at the compressive strains required. The second method involved designing the liner so expansion at operating pressure is equal to the contraction from the cryogenic propellant. The final and recommended method was to use a low level autofrettage not critical for buckling and pressurization of the tank to counteract the contraction.

There are several design standards available for composite pressure vessels with metal liners, including Department of Transportation (DOT) FRP-1(for fiberglass), DOT-CFFC (for carbon/epoxy) and AIAA S-081. At this time, there is no known standard for composite feedlines with metal liners.

Feedline Loads

The data for the feedline section from station $X_t = 1856$ to 1958 (Table 1) represents the loads experienced by the feedline section in the 8.6 minutes that the ET is providing propellant to the Space Shuttle Main Engines (SSMEs). To be conservative, the worst case of each load component (3 moment, 2 shear, 1 axial, 1 pressure) was taken and multiplied by a 1.5 factor to arrive at the load conditions for sizing. There is also a worst case static pressure of 235 psi to be used for hoop tension only, and not to be combined with any other load.

Typical composite feedline design practices require a proof (1.5x) and burst (2.5x) pressure factor be applied to the maximum expected operating pressure (MEOP) [5]. In production, all feedlines are pressurized to the proof pressure to “prove” its capability, while only one of the feedlines in that production lot is taken to burst pressure. Obviously, if a feedline fails at or above the burst pressure, it is considered acceptable. Because it would be very complicated to test the feedline for 235 psi in hoop tension only, it seems appropriate to use this value as the MEOP and test both hoop and longitudinal loads. Hence, proof and burst pressures are 353 psi and 588 psi, respectively.

It is assumed that the feedline is at -321°F when LOX is flowing. When LOX is not flowing, the liner is expected to be at ambient temperature. The maximum ambient temperature range is approximately 0°F to 150°F , of which the high temperature becomes critical for sizing. Vibration, implosion, low cycle fatigue and handling loads were not in the scope of this study.

Materials and Fabrication

In order to be lightweight yet conservative, IM7/977-6 carbon/epoxy fabric was chosen as it has been used extensively in cryogenic applications [5, 6, 7]. This toughened epoxy has a curing temperature range of 275F to 350F, but could be cured at lower temperatures (240F) with a corresponding reduction in T_g and matrix dominated properties. Hand lay up was selected over other process such as filament winding, fiber placement and RTM solely from the standpoint of simplicity. NASA Marshall currently fabricates feedlines for testing using this method, having considerable experience base with this material. Table 2 shows the material properties of the prepreg 5-harness satin fabric at room temperature. For simplicity, the same properties were used for cryogenic temperature since the differences are expected to be small.

Aluminum 2219, Stainless Steel 321 and Inconel 718 have been used extensively for spacecraft LOX applications and were suggested as liner candidates at the beginning of the investigation. Their material properties are shown in Table 3 at room temperature ambient (RTA). These metals have no LOX compatibility problems at the pressures of the ET feedline [8]. Despite its resistance to corrosion, stainless steel was removed from the list because of its low yield strength and relatively high density.

Low thermal expansion metals such as Invar 36, Incoloy 908 and other nickel alloys were also considered. Invar 36 (36% iron, 64% nickel) is frequently used for cryogenic applications such as the polar bosses (end caps) in composite pressure vessels. Despite Invar 36 having a low 1.5 microstrains/F CTE, it has a very low elastic strain range (approximately 1500 microstrains) and Invar's CTE is dependent on the amount of plastic strain in the material. Although this raises questions about the CTE that would result from the autofrettage process, Invar 36 was included in the study.

Incoloy 908 also has a low CTE, 4.2 microstrains/F, and has been used in superconductivity applications. Due to a lack of material properties, it was not included in the study, however, this material certainly deserves closer scrutiny.

To make the feedline assembly out of the materials above, a combination of welding, machining and chemical milling are options for fabrication. Electron beam, resistance seam, variable polarity plasma arc (VPPA) and friction stir welding (FSW) are probably the best welding candidates at this time, having been used on thin metal liners in other applications. The tube section with larger thickness than the final thickness could be made from spinning an extrusion or welded from sheet. A machined part of the flanges and a small section of the tube could then be welded to the tube section. (Figure 2) After welding and heat treatment, the liner would be mounted securely onto a washable mandrel (e.g. sand mandrel, Caremold) and chemically milled to the desired thickness. With the proper surface preparation, the adhesive and composite material would then be laid up on the liner to be vacuum bagged and cured in the autoclave. After curing, the mandrel is washed out with a high-pressure jet of water.

Electroplated nickel liners are currently being investigated at NASA Marshall for cryogenic tanks. This process consists of passing a current between two electrodes that are immersed in a conductive, aqueous solution of nickel salts. The flow of direct current causes one of the electrodes (anode) to dissolve and the other electrode (cathode) to become covered with nickel. For most engineering applications, the nickel sulfamate solution is used because of the low internal stress of the deposits, high rates of deposition and superior throwing power.

Electroplated nickel and nickel alloy were added to the list candidates because of their simplicity and low cost. (Table 3) A liner can be plated directly onto a washable mandrel by applying a conductive coating to the mandrel surface. However, material properties of

electroplated metals are difficult to find and may vary considerably from one manufacturer to another. The highest room temperature material properties were obtained from Sandia National Laboratories, which has a technique to increase material properties by varying grain sizes. Sandia has also electroplated nickel with 20% iron, which offers much lower CTE than pure nickel and possibly better strength. To approximate the properties of this material, the same values were used as pure nickel except the CTEs were changed to reflect this nickel alloy. In the absence of properties at high and low temperature, the same normalized strength, modulus and CTE ratios of aluminum 2219 were applied to nickel and nickel alloy.

Other metal surfacing techniques were investigated such as thermal spraying, chemical milling, physical vapor deposition (PVD), chemical vapor deposition (CVD) and sputtering. At present, these techniques are judged as less promising because of low material properties, permeability, and difficult manufacturing scale-up.

Polymer liners offer the advantage of being lightweight and LOX compatible but [1] tried many types (teflon, mylar, aluminized mylar) without success in the X-34 LOX tank application. No polymer liner candidates were investigated, because any polymer would have to undergo expensive LOX compatibility testing.

Buckling

Two areas of concern for buckling of the liner occur during autoclave curing and after autofrettage at zero pressure with high ambient temperature. In the first instance, the liner attempts to expand due to curing temperature but is assumed to be stable because of restraint from the vacuum bag and autoclave pressure. In the second, the composite outer casing is compressing the liner because autofrettage and high ambient temperature has increased the

liner's size. If the liner is not bonded to the casing, Glock [9] and Kabir [10] provide solutions for the critical pressure in which the liner will buckle. These solutions are as follows.

$$P_{CR,Glock} = 0.969 \left(\frac{AR^2}{I} \right)^{\frac{2}{5}} \left(\frac{EI}{R^3} \right), \quad P_{CR,Kabir} = \frac{Et^2}{3R^2(1-\nu^2)^{1/2}} \quad (1)$$

These equations are very similar for a liner section of unit width and $\nu = 0.3$.

If the liner is continuously bonded to the outer casing with a film epoxy, the flatwise tensile strength of the adhesive can resist buckling and the liner can achieve the compressive yield strength. Film adhesive candidates include FM73, FM 300, EA 9696, and EA9695. Using 350F cure film adhesive FM73, an extremely thin autofrettaged aluminum liner, 0.005", was achieved without buckling on an 18" diameter pressure vessel by Carleton PTD. Dexter Hysol EA9696 was chosen because it was used successfully by [3] for an aluminum foil liner and because of its high material properties.

According to manufacturer's specifications, the flatwise tensile strength is 1200 psi for this system (Table 4). This value must be used with care since the data reflects exceptional metal-to-metal sample preparation, etc. A conservative safety factor of 2.0 gives a flatwise tensile strength of 600 psi. If there are no significant voids between the liner and the outer casing, it is reasonable to assume the 600 psi adhesive will restrain any lateral movement of the liner, preventing buckling. The neat resin tensile strength was estimated to be approximately 10ksi and used as maximum Von Mises stress. Unfortunately, the CTE for this epoxy is probably very high compared to the liner and composite, estimated to be 30 microstrains/F from typical epoxy data.

One Dimensional Analysis

The straight feedline was divided into three sections (Figure 3). The center section is completely autofrettaged, the transition section is partially autofrettaged, and flange section is has no autofrettage. The one dimensional analysis was done on center and flange sections only.

Several assumptions were made to reduce the center section to a 1 dimensional problem. This provided a quick means to find the most promising liner materials and a way to visualize the entire loading envelope. It was assumed that the center section behaves like an infinitely long cylinder with no end effects. Only hoop loads were applied to check the critical stresses and strains. The maximum principal stress criterion was sufficient for the liner and maximum strain criterion for the composite. The elastic-perfectly plastic hardening model was used to describe the liner behavior with no Bauschinger Effect present (isotropic strain hardening was assumed). After straining the liner plastically in tension, the full compressive yield strength can be reached upon reverse loading. Lastly, sliding contact was assumed between the liner and the composite (no film adhesive).

For pressure vessels which have thickness/inner radius ≤ 0.10 , basic mechanics equations for hoop and longitudinal stress are accurate within 5%.

$$\sigma_{hoop} = \frac{Pr}{t} , \quad \sigma_{long} = \frac{Pr}{2t} \quad (2)$$

In the hoop direction, the equilibrium equation for a pressure vessel with composite outer casing and metallic liner can be described as

$$\sigma_m t_m + \sigma_c t_c = Pr \quad (3)$$

The following equation is used to describe the hoop stress after autofrettage.

$$\sigma_m = E(\varepsilon_m - \varepsilon_0) \quad (4)$$

The change in stress due to temperature is given by

$$\sigma = E(\varepsilon_m + \varepsilon_T), \quad \varepsilon_T = \alpha_m \Delta T \quad (5)$$

The strain changes can be combined to give the basic stress-strain relationship in an autofrettaged pressure vessel with temperature difference.

$$\sigma = E(\varepsilon_m - \varepsilon_0 + \varepsilon_T) \quad (6)$$

For the case of zero pressure after autofrettage and cryogenic temperature drop, equation (3) and (4) can be used to obtain the resulting strain in the composite and the metal liner.

$$\varepsilon_m = \varepsilon_c = \frac{t_m E_m (\varepsilon_0 - \varepsilon_T)}{t_c E_c + t_m E_m} \quad (7)$$

After some iteration, it was found that a [liner, 0/90, 90/0] lay-up with no ± 45 layers was sufficient because of low shear from flight loads. Six points in the loading of the feedline were chosen to quantify relative performance of each material combination as shown in Figure 4.

The first critical loading point represents the stress and strain of the metal liner during the autoclave cure and is shown with an “×” in Figure 4. Thermal compressive stresses are induced because the autoclave/vacuum bag pressure restrain movement and buckling of the liner, which is supported by the washable mandrel. In reality, the CTE of the mandrel is slightly positive (e.g. 1.9 microstrains/F for Caremold), but is assumed to be zero to show the worst-case compressive stress in the liner. The safety factor for the metal liner’s compressive yield, to its actual stress, must be no less than 1.05. The composite is assumed to provide no restraint of the liner until curing is complete, therefore its stress and strain are zero. A second “×” is shown at the origin to represent the composite when the metal liner is at point 1.

All feedlines in a production lot are tested to proof pressure which is the second critical point shown as a pair of squares. Typically, this pressure is required to be 1.5 x MEOP, but in

this study it is adjusted to this value or greater in order to keep the desired amount of residual compressive strain (5% of the yield strain) at zero pressure and -298°F temperature. (See Point 4c in Figure 4.)

One feedline in the production lot is tested to burst pressure at room temperature which is $2.5 \times \text{MEOP}$. This feedline must fail at burst or a higher pressure to qualify and is shown as pair of diamonds, the third critical point. Since the metal liner has yielded and composite failure is the concern, the maximum strain criterion in the hoop direction is used to determine the burst pressure.

The remaining feedlines in a production lot may be kept in storage at room temperature with ambient pressure as depicted by Point 4a and shown as a pair of solid circles. Here, the composite has residual tensile stress while the liner has compressive stress due to the previous autofrettage. A feedline may then be installed on a flight vehicle exposed to “high” environmental temperature (150°F) such as on a launch pad with direct sunlight. The induced thermal compressive stress in the liner (Point 4b) is shown as a solid circle and is typically the liner’s sizing condition. The safety factor of the metal liner’s compressive yield to its actual stress must be greater than 1.05. It should be noted that the equivalent external pressure, creating the compressive stress, far exceeds the critical buckling pressure of an unbonded liner (Equation 1). Since the liner is continuously bonded, buckling is improbable.

During launch procedures, a feedline may be exposed to LOX but at very low pressures, i.e. engine chilldown. This Point is 4c and is also shown as a pair of solid circles. As mentioned earlier, the hoop direction compressive strain after thermal contraction is held to at least 5% of the yield strain to prevent separation of the liner from the composite.

Maximum flight loads are applied at Point 5 and are shown as solid triangles. The curve for the metallic liner shows a higher yield strength and slightly higher stiffness due to operation at LOX temperature. The tensile loads are the critical factor and must be at least 1.05. These loads were applied on the composite laminate and metal liner using CADEC [11] software. In all cases, these loads are low compared to burst pressures so composite failure criteria is not examined. As described earlier, the screening procedure is only one-dimensional, so metals failure criteria (i.e. Von Mises, Tresca) are not used and only the maximum stress in hoop direction is compared to tensile yield stress.

Point 6, shown as a solid diamond, is at LOX temperature and burst pressure where the safety factor for the composite must still be at least 2.5 times the MEOP. Again, the maximum strain criterion in the hoop direction is used to determine the safety factor.

Table 5 shows the results of the six-point analysis, keeping the required safety factors. The autoclave temperature was reduced to 240F for the high CTE materials (aluminum and nickel) to keep the required safety factor at Point 1. The percentage of weight saved versus the all-aluminum feedline is shown for each material combination on a unit length basis. (Positive percentages indicate weight saved.) Because of its low yield strength capability, Invar 36 could not show a positive weight savings and was consequently dropped from the evaluation. The remaining candidates all showed potentially high weight savings (36%-45%) and consequently moved to the flange section evaluation.

Because the focus of this investigation is autofrettage in the main feedline section, a simple design was used for the flange and transition section. (Figure 5) The preliminary design has a .75" thick flange (52 plies) and a 0.5" inner flange radius. Since the sizing condition for the flange is the allowable deflection to give proper sealing between bolts, the flange thickness

was chosen to be the same as the original all-aluminum flange because the composite stiffness is approximately the same as the aluminum. All plies in the flange continue through the radius without termination to allow for easier manufacturing and reduce stress concentrations. The typically accepted minimum ply drop off ratio of 1:16 – 1:20 was used to transition from the thick flange down to the feedline wall thickness as quickly as possible.

It should be noted that the simple composite flange and transition in Figure 5 is heavier than the original aluminum flange in Figure 6. Optimizing the ply schedule and in-depth evaluation of sealing requirements can reduce the weight of the flange so that the overall weight of the feedline is competitive with the all-metal feedline. For example, [7] used ply drop offs in the flange radius to reduce wall thickness for bolt head clearance and reduce weight (Figure 7). This optimization is not in the scope of this study but is mentioned here for future work.

Unlike the center section, the flange section is so thick that it does not expand adequately to allow autofrettage of the liner. A worst-case scenario could involve the liner having no compressive preload from autofrettage, and the full thermal strain caused from an excursion from RTA to –298F being applied to the liner in both longitudinal and hoop directions. In this case, the adhesive restrains the liner from separating from the composite. The theoretical temperature-induced stress (assuming no plasticity) that would be achieved can be described below,

$$\sigma_{Biaxial} = \frac{E\alpha\Delta T}{1 - \nu} \quad (8)$$

is required to have at least a 1.05 safety factor from yield, or $F_{ty} \geq 1.05\sigma_{Biaxial}$.

From Table 6, aluminum and nickel's high CTEs cause their safety factors to fall below 1.0, while Inconel 718 and the nickel alloy's relatively low CTEs keep their strength ratios above 1.05.

Ordinarily, aluminum and nickel would be removed from the evaluation, but it is of interest to see if yielding at a temperature lower than LOX could cause a favorable residual compressive stress distribution at LOX temperature. In order to study “autofrettage by temperature”, aluminum and nickel were included in the finite element study.

Two Dimensional Analysis

The accuracy of the 1-D results verified to be within 3% by making a simple axisymmetric model using parabolic, solid elements. Gap elements were used between the liner and composite elements allowing frictionless sliding contact between the two materials. The mesh was generated in IDEAS MS 8m2 and solved in ABAQUS because of the temperature and plasticity options needed in subsequent analysis. Again, the elastic-perfectly plastic model was used for the metal because the plastic strains were relatively small and because it allowed better comparison with the preliminary analysis.

Since the center section experiences 2-D loading, axisymmetric models were made with liner and composite fused together with film epoxy to simulate points 1, 2, 3, 4a, 4b, 4c, and 6 (Figure 8). Models were made varying the number of elements (1, 2, 4) through the thickness (TTT) of the liner and very little variation were found in the results. The previous 1-D hoop stress approximations were within 10% of the hoop stresses, except at zero pressure and -298F (Point 4c). Because of the inclusion of film adhesive in the model and the low absolute value of the stress at this point, the error is within 50%. A 3D model would be required to fully simulate flight loads (Point 5), but because of time restraints, this load condition was verified by using CADEC software [11].

The center section FE results (Table 7) show that the stress in the liner for all three directions is negative at RT and zero pressure. This is because autofrettage has yielded the liner plastically in longitudinal and hoop directions (Point 4a). After exposure to LOX, the liner shrinks but the TTT stress is still compressive (Point 4c), showing that the liner did not “pull away” from the composite. At this point, the thermal shrinkage was large enough to change the liner *longitudinal* compressive stress to tensile stress, as expected. The critical point for sizing the liner, however, is at zero pressure and highest ambient temperature (Table 8, Point 4b). The SFs are acceptable and very close to the preliminary analysis.

The manufacturer reports that adhesive material properties are best for 0.010” thickness (0.060 psf) versus 0.005” thickness (0.030 psf). FE model results show that the higher thickness adhesive tends to reduce stresses by introducing more compliance between the composite and liner. The reductions were on the order of 5% or less.

The model was restrained in the vertical direction by a “back-up ring” and by the opposite mating flange. The back-up ring is held in place by the bolts and is commonly used during testing, but for the final analysis, a 3-D FE model would be made with only bolts. Both mating flange and back-up ring have gap elements separating them from the feedline.

Pressure is effective in causing autofrettage in the center section up to the beginning of the ply drop off area. Here, the transition to no autofrettage is quite small (Figure 8) for all the materials. At cryogenic temperature, the feedline reflexes inward toward the center of the pipe in the transition section.

The FE results confirm that the flange, radius and remainder of the ply drop off areas do not experience autofrettage from pressure. The main loading in these areas comes from LOX temperature-induced strain, which causes yielding in the high CTE Aluminum 2219-T62 and

nickel liners, but not in Inconel 718 or nickel alloy 8020. The safety factors for Inconel and nickel alloy liners are shown in Table 9 and are similar to estimates made in Table 6. To make the safety factors for aluminum and nickel greater than 1.0, autofrettage by temperature is used as described in the next section.

Due to the high CTE of the epoxy and the exposed edges, the stresses in the film epoxy at the flange tip are high when at low temperature. Many alternatives are available to prevent cracking of the bondline, such as tapering the liner and making a liner lip for restraint. These optimization steps were not pursued further in this study.

Autofrettage By Temperature

For a robust design, the yielding that the aluminum and nickel liners exhibit (Table 6) is undesirable during operation because of the reduction in low-cycle fatigue life and chance of premature failure. However, if the aluminum and nickel are first cooled to LN2 temperature (-320F), the liners will then operate in the elastic region at LOX temperature (-298F). This is because the combination of adhesive restraint and temperature drop to LN2 has yielded the liner, allowing the material to have the safety factors listed in Table 9 when at LOX temperature. As an important check, the safety factors are shown for zero pressure and maximum ambient temperature (150F) in Table 10. Thus, Tables 9 and 10 show that aluminum and nickel in the flange/transition sections do not yield at zero pressure from -298F to 150F, suggesting that “autofrettage by temperature” is an alternative when CTEs are high and pressure cannot be used to cause autofrettage.

Another possibility for the aluminum liner is to use all metal flanges and have composite overwrap only on the center section (Figure 9). This will remove the CTE problem at the

flange/transition and autofrettage will be used in the center section. This design was used successfully by [2] for the oil industry where the main challenge was high pressure (15 ksi) instead of CTE mismatches.

Discussion and Conclusions

From the stress standpoint, low CTE metal liners (less than 7 microstrains/F) with high elastic strain capability (4000+ microstrains) are definitely preferred in autofrettaged composite feedline. Materials such as Inconel 718 or other nickel alloy fit this requirement, but introduce some complications. Inconel 718 can be welded and chemically milled, but requires high temperature heat treatment to recover parent metal strength, which may be logistically difficult for a large, thin part. Electroplated nickel alloy could be produced much more economically, requiring no welding and having the potential for making *curved feedlines*. However, the actual elastic strain capability and the material porosity remain to be determined with future work. The high CTE metal liners, such as aluminum and nickel, can avoid yielding with “autofrettage by temperature”, or in the case of aluminum, all-metal flanges with composite overwrap in center section. This technique must be planned so that there is no compressive yielding at the expected maximum operating temperature.

In conclusion, this study shows that autofrettage is a viable process to allow the design of metal liners in composite feedlines, using the current state of the art in materials and processes. Further optimization and material testing are necessary to closely determine the weight and cost savings. Future advances in electroplating, surfacing and joining technology will serve to strengthen the benefits that autofrettage can bring to a cryogenic application.

References

1. Black, S., 2000, "X-34 composite liquid oxygen tank a first," High Performance Composites, Vol 8, No 4, 52-54.
2. Briers, W., 2001, "The design and analysis of a hybrid steel/composite pipe for high pressure application," MS Thesis, West Virginia University, Mechanical Aerospace Engineering Department.
3. Warner, M.J., 2000, "0.94-Meter (37 in) Cryogenic Demonstration Tank," 45th International SAMPE Symposium, 2285-2292.
4. MacConochie, I., et.al., 1984, "Reusable cryogenic-liquid tank with replaceable liner," NASA Tech Brief LAR-14172.
5. Tygielski, P., 1997, "Development of a Composite Feedline for the Clipper Graham Vehicle," 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 97-2673.
6. Robinson, M., 1994, "Composite cryogenic tank development," AIAA-94-1375-CP.
7. Harvey, W.A., Kremer, J.S., 1997, "Design, process development, and fabrication of an all IM7/977-2 12 inch diameter pressurized fuel line required to operate at -423F while bolted to an aluminum valve," 42nd International SAMPE Symposium, 839-853.
8. Bond, A., et.al., 1983, "Design guide for high pressure oxygen systems," NASA Reference Publication 1113,.
9. Glock, D., 1977, "Überkritisches Verhalten eines starr ummantelten Kreisrohres bei Wasserdruck von aussen und Temperaturdehnung," Der Stahlbau, Vol 7, 212-217. ("The over-critical behavior of a rigidly encased pipe under outer-hydrostatic pressure and thermo-stretch," translated by Li, Shi.)
10. Kabir, M.Z., 2000, "Finite element analysis of composite pressure vessels with a load sharing metallic liner," Composite Structures, 49 (2000), 247-255.
11. Barbero, E. J., 1999, "Introduction to Composite Materials Design," Taylor & Francis, Philadelphia.

Table 1 Flight Loads and Worst Case Static Hoop Pressure for Feedline Section.

Load Component	Units	Liftoff	Liftoff Totals	Boost Totals	BA Totals
Mx	[in-lb]	25,080	7,420	6,091	6,272
My	[in-lb]	76,667	36,451	66,790	59,312
Mz	[in-lb]	65,996	49,454	55,794	51,144
Px max	[lb]	6,619	21,968	16,124	15,606
Px min	[lb]		-174	-1,506	1,763
Vy	[lb]	1,805	1,270	1,584	1,291
Vz	[lb]	1,252	1,059	1,585	1,637
Pressure ^a	[psi]	152	152	152	152

^a Worst case static hoop pressure, not to be combined with other loads = 235 psi

Table 2 Typical Room Temperature Properties of IM7/977-6 5HS Fabric.

Material		IM7/977-6 Prepreg 5HS RT
E1, E2	[Msi]	10.4
G12	[Msi]	0.66
Ftu	[ksi]	144
Fcy	[ksi]	84
CTE	[$\mu\text{in/in/F}$]	~0
density	[lb/in ³]	0.0488
ϵ ten. ult.	[$\mu\text{in/in}$]	13846
Cured Ply Thick	[in]	0.0144

Table 3 Typical Room Temperature Properties of Liner Candidates.

	E	F _{tu}	F _{ty}	F _{cy}	CTE	density	ε ten. yield	ε ten. ult.
	[Msi]	[ksi]	[ksi]	[ksi]	[μin/in/F]	[lb/in ³]	[μin/in]	[μin/in]
Inconel 718	29.4	180	145.0	155.0	6.80	0.297	4932	120000
Al 2219-T62	10.5	54	36.0	37.0	12.20	0.102	3429	100000
Stainless 321	29.5	200	45.6	45.6	9.20	0.29	1546	460000
Invar 36	21.7	60	35.0	35.0	1.50	0.291	1613	430000
Electroplated Nickel	21.8	132	87.0	87.0	13.00	0.322	3999	90000
Electroplated Ni-Fe 8020 ^b	21.0	~130	~90	~90	5-13	~.300	~4000	N/A
Electroplated Invar 36 ^b	21.0	~130	~90	~90	1.50	~.300	N/A	N/A
Incoloy 902, 903, 908	25-29	175	110.0	110.0	4.20	0.291	4400	250000

^b Estimated properties.

Table 4 Typical Room Temperature Properties of EA9696 Film Adhesive, 0.060 psf.

Material		EA 9696
		RT
Flatwise Ten.	[psi]	1,200
Lap Shear	[psi]	6,300
Tensile Strength ^c	[psi]	10,000
Cure Temp	[F]	225-265
CTE ^c	[μ in/in/F]	30
Film Wt.	[psf]	0.060

^c Estimated Properties

Table 5 Center Section One Dimensional Analysis Summary.

	Inconel	2219	Nickel	Nickel Alloy	Invar36	2219 only
composite thickness, [in]	0.0288	0.0288	0.0288	0.0288	0.115	0.000
liner thickness, [in]	0.010	0.025	0.010	0.010	0.010	0.071
CTE @ -298F, [μ in/in/F]	5.50	10.00	10.66	3.96	1.50	10.00
Autoclave Curing Temperature, [F]	265	240	240	265	265	---
1. Metal comp. SF @ 100 psi, curing temp	2.8	1.05	1.05	2.5	5.7	---
2. Proof Factor @ 77F	2.0	1.7	1.8	1.5	1.8	1.2
3. Burst Factor @ 77F	2.8	2.5	2.5	2.5	8.5	1.9
4a. Metal compressive SF @ 0 psi, 77F	3.1	1.4	1.3	2.1	1.6	---
4b. Metal compressive SF @ 0 psi, 150F	2.6	1.2	1.08	1.8	1.5	---
5. Metal Flight loads SF, -298F	2.1	1.4	1.5	1.6	2.7	1.8
6. Burst Factor @ -298F	2.9	2.6	2.6	2.6	8.6	2.3
% saved of Al weight per unit length	40%	45%	36%	36%	-18%	0%

**Table 6 Theoretical Stress at Flange/Transition Section, 77F to -298F when
material is restrained biaxially.**

	Inconel	Al 2219	Nickel	Nickel Alloy
Theoretical Stress [psi]	90,529	65,821	145,409	54,025
Fty @ -298F [psi]	166,750	42,120	102,686	102,686
Safety Factor	1.84	0.64	0.71	1.90

Table 7 Center Section Component Stresses in Liner Before and After Exposure to LOX.

	Direction	Inconel	Al 2219	Nickel	Nickel Alloy
		[psi]	[psi]	[psi]	[psi]
Point 4a, RT, 0 psi	Hoop	-46540	-28330	-72610	-44840
	Long.	-17750	-13530	-36010	-20720
	TTT	-55	-83	-85	-52
Point 4c, -298F, 0 psi	Hoop	-10040	-2741	-12550	-25270
	Long.	29270	13150	17530	369
	TTT	-12	-8	-14	-30

Table 8 Center Section Von Mises Stress at Zero Pressure and Highest Ambient Temperature.

		Inconel	Al 2219	Nickel	Nickel Alloy
Point 4b, 150F, 0 psi	Von Mises [psi]	47,820	29,830	75,790	42,960
	Fcy @ 150F [psi]	151,900	35,890	82,671	82,671
	Safety Factor	3.18	1.20	1.09	1.92

Table 9 Transition/Flange Section Von Mises Stress in Liner at Zero Pressure, -298F.

	Inconel	Al 2219 ^d	Nickel ^d	Nickel Alloy
Von Mises, [psi]	89,030	41,030	97,700	53,560
Fty @ -298F, [psi]	166,750	42,120	102,686	102,686
Safety Factor	1.87	1.03	1.05	1.92

^d These materials have "autofrettage by temperature"

Table 10 Flange/Transition Section Von Mises Stress at Zero Pressure, 150F.

	Inconel	Al 2219 ^e	Nickel ^e	Nickel Alloy
Von Mises, [psi]	20,420	34,440	72,080	11,220
Fcy @ 150F, [psi]	151,900	35,890	82,671	82,671
Safety Factor	7.44	1.04	1.15	7.37

^e These materials have "autofrettage by temperature"

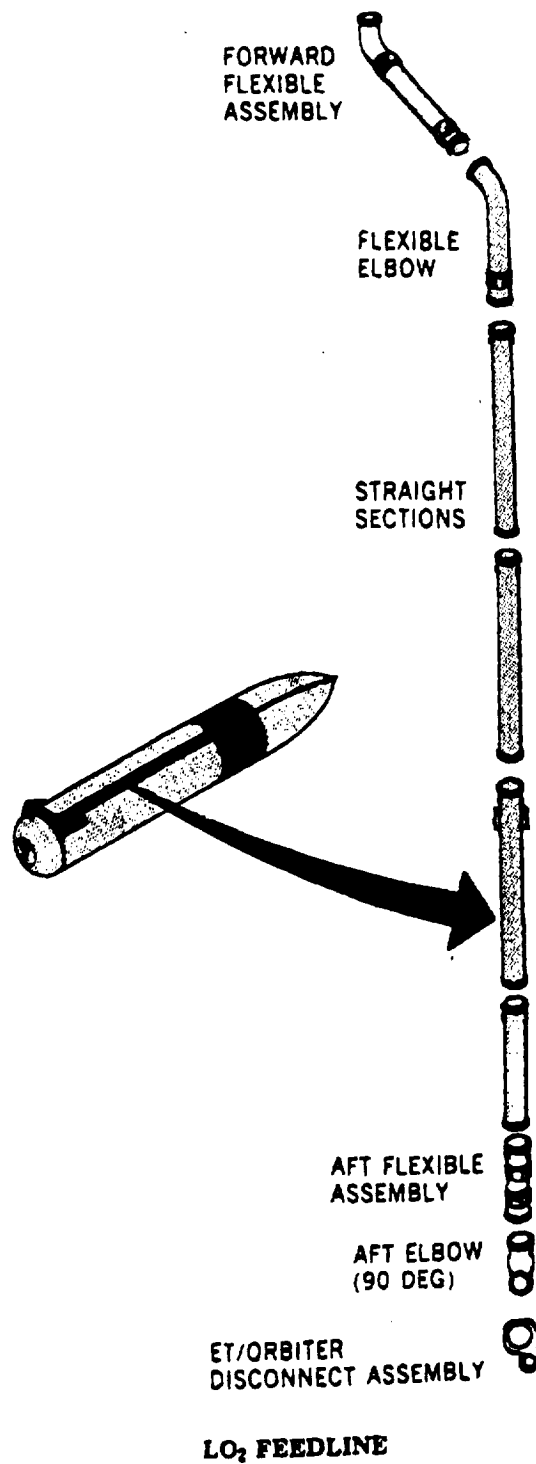


Figure 1 Straight Section of Feedline chosen for Study.

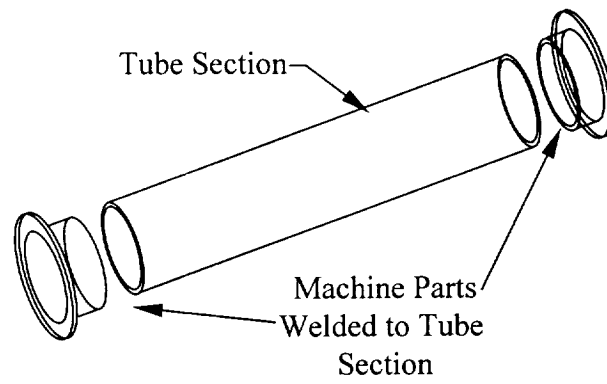


Figure 2 Flange welded to Tube section.

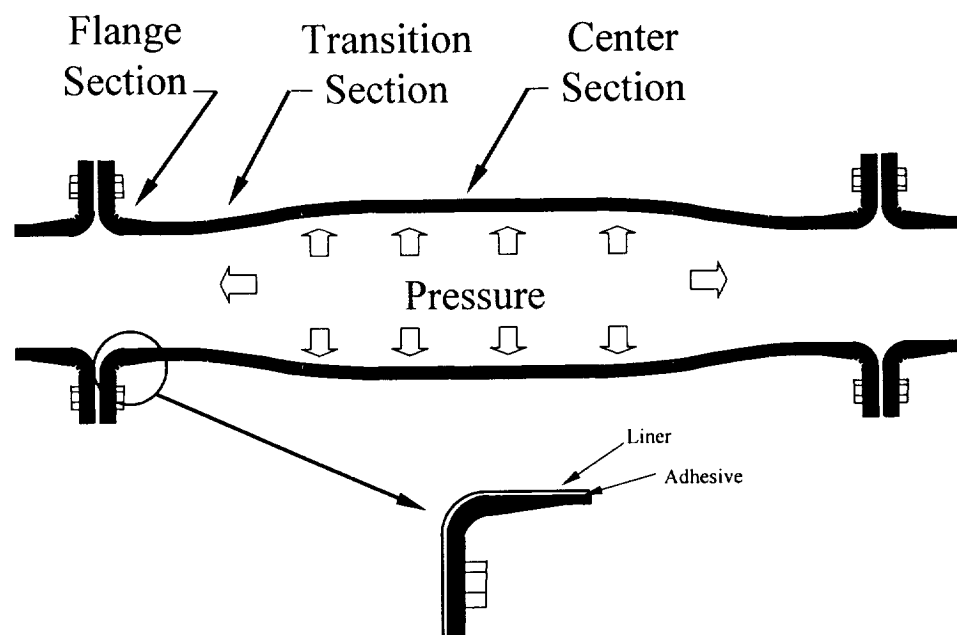


Figure 3 Feedline divided into three sections.

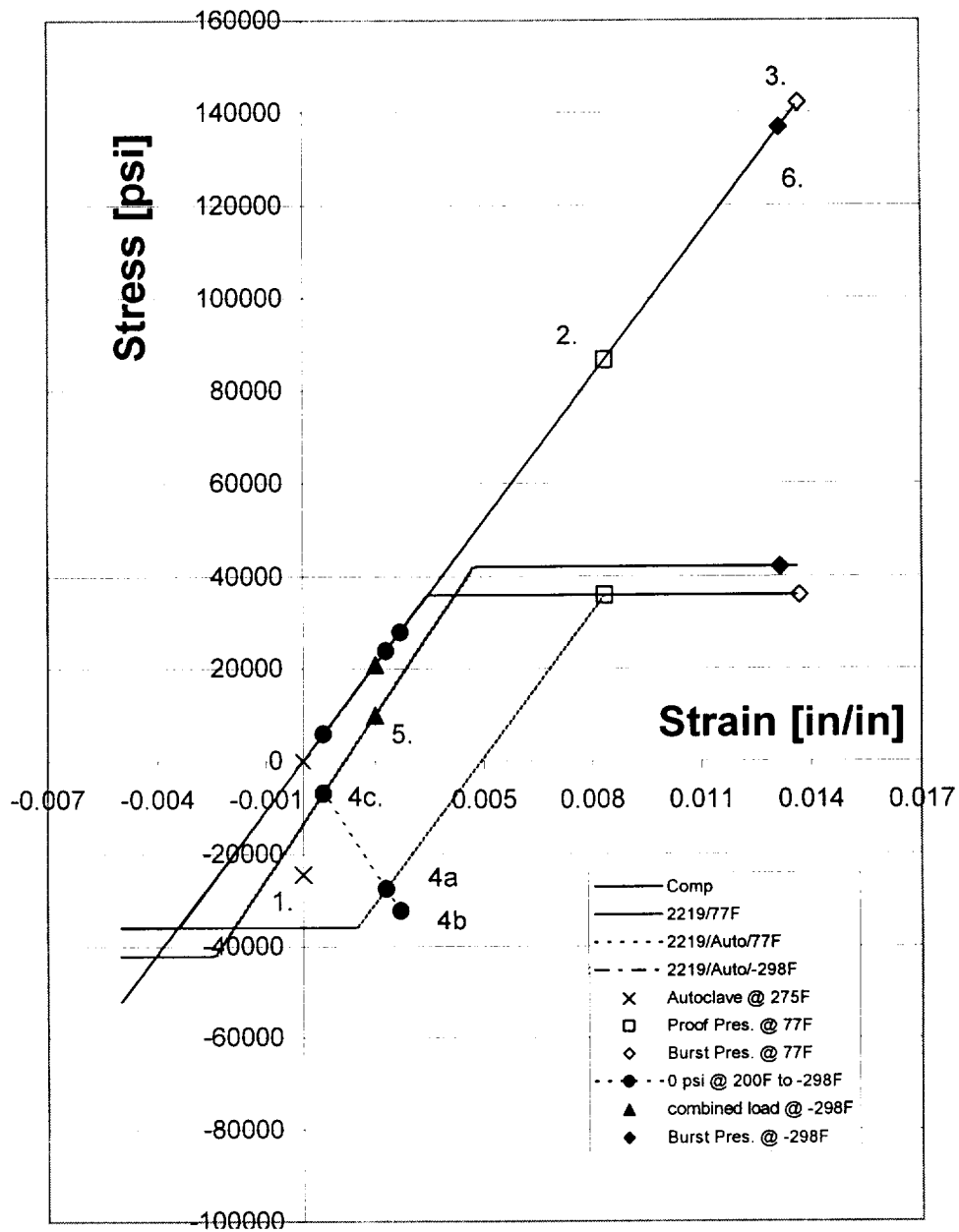


Figure 4 Six Point Loading for Center Section.

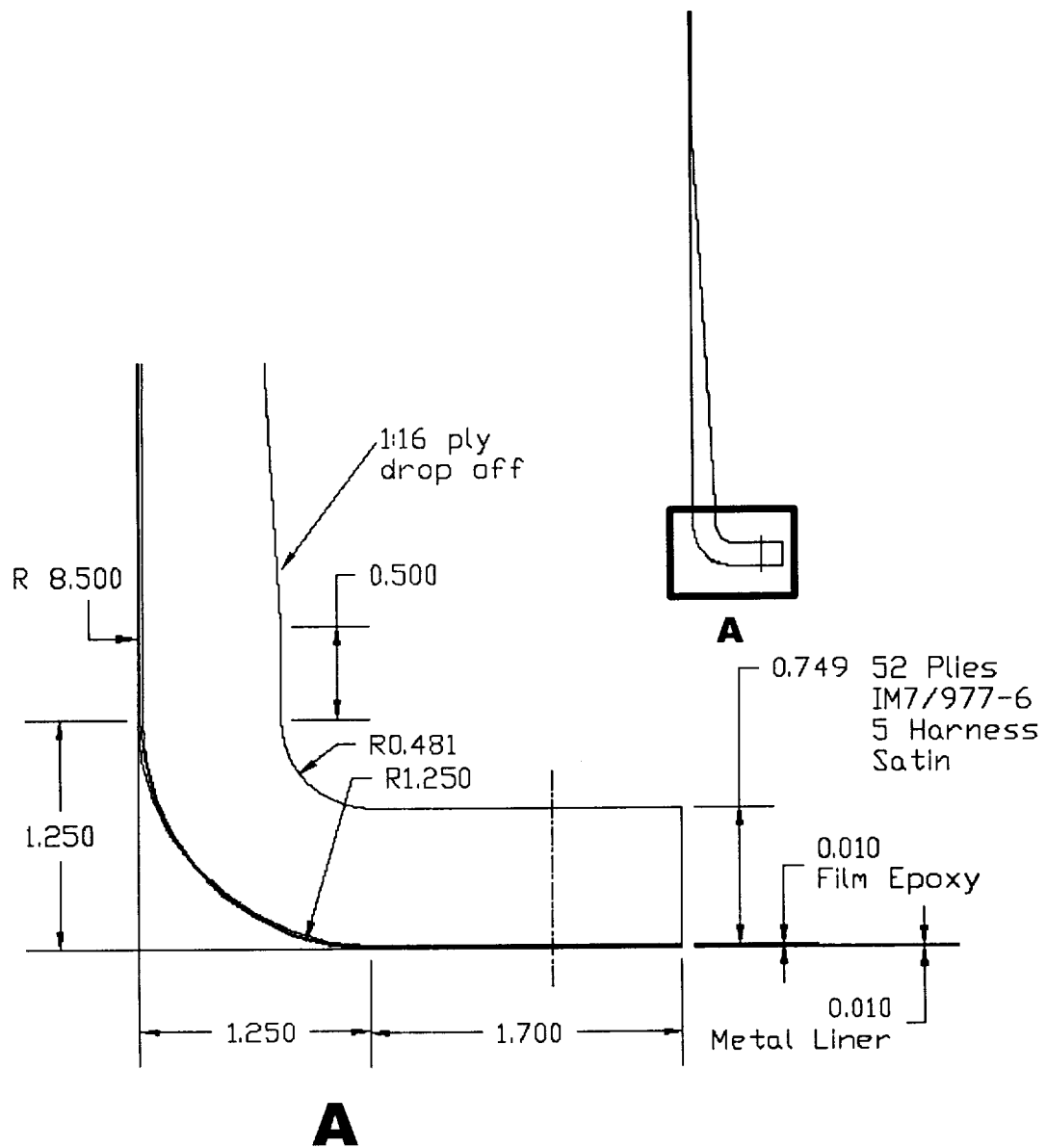
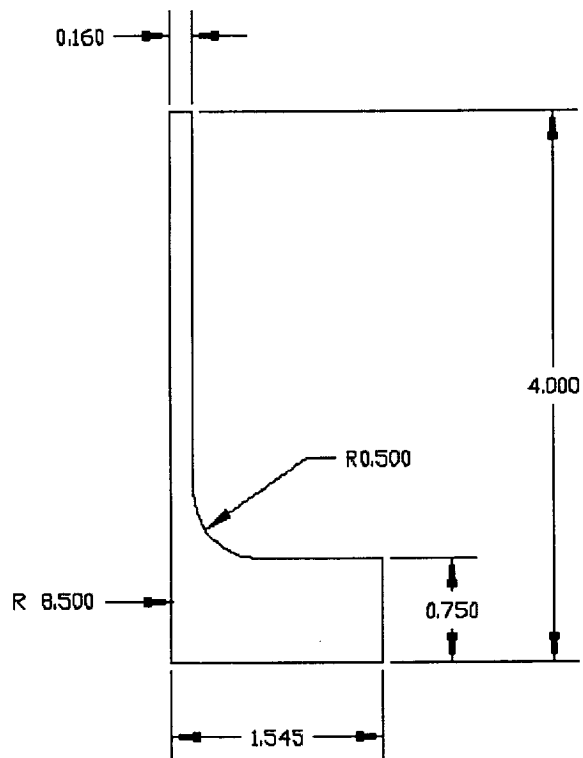


Figure 5 Preliminary Flange Design.



**Figure 6 All Aluminum Shuttle External Tank LOX
Feedline Flange Dimensions.**

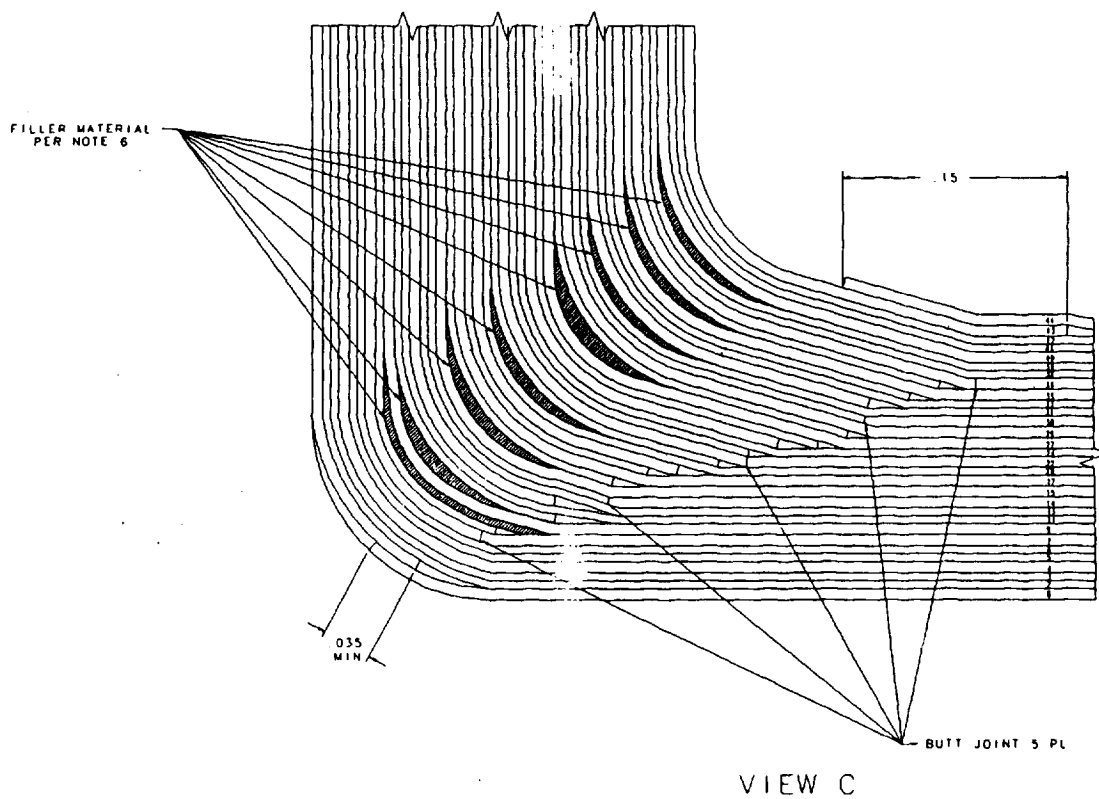


Figure 7 Flange Weight Optimization using Ply Drop Offs in Flange Radius [7].

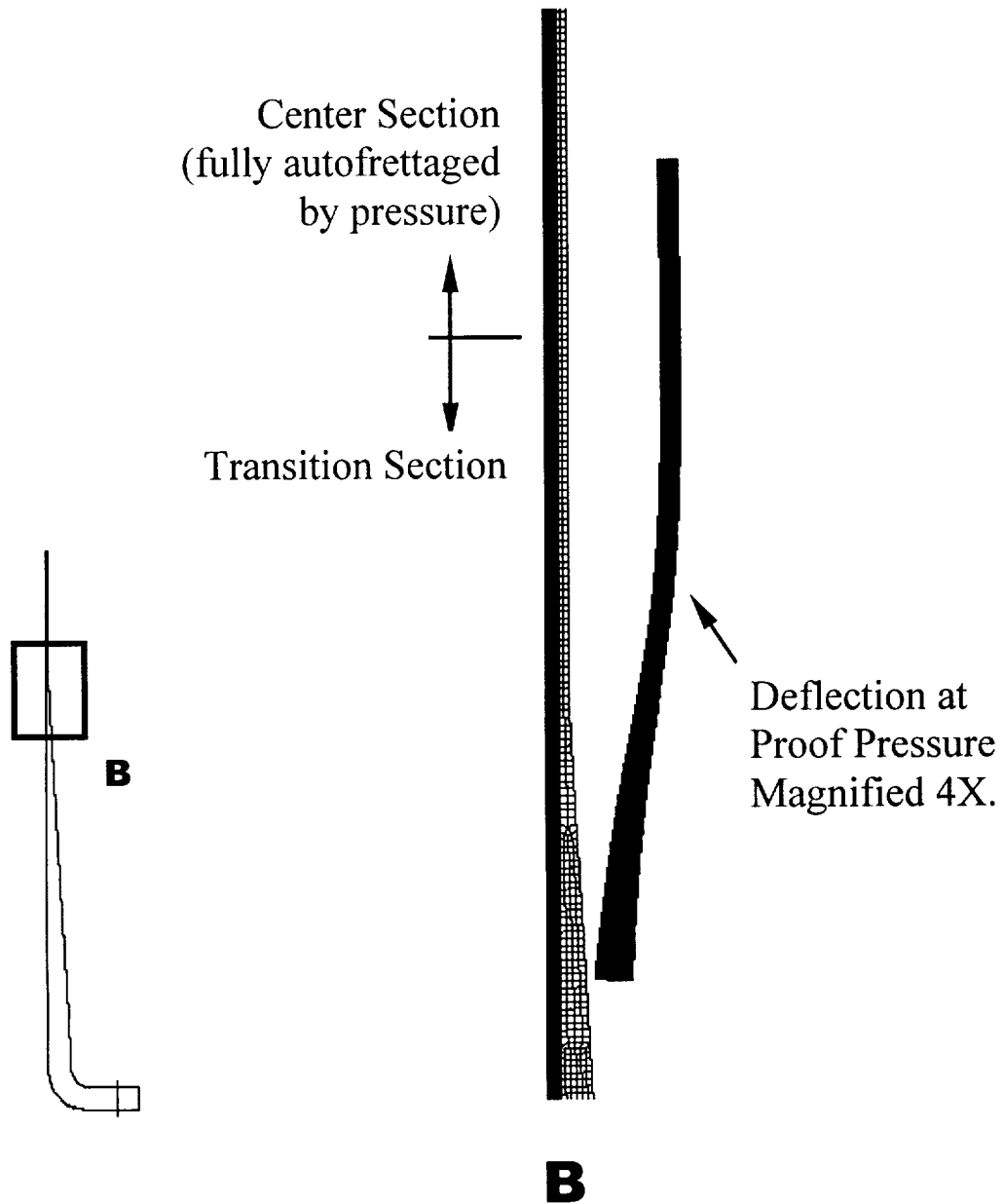


Figure 8 Deformed Transition Section at Proof Pressure, Magnified 4X.

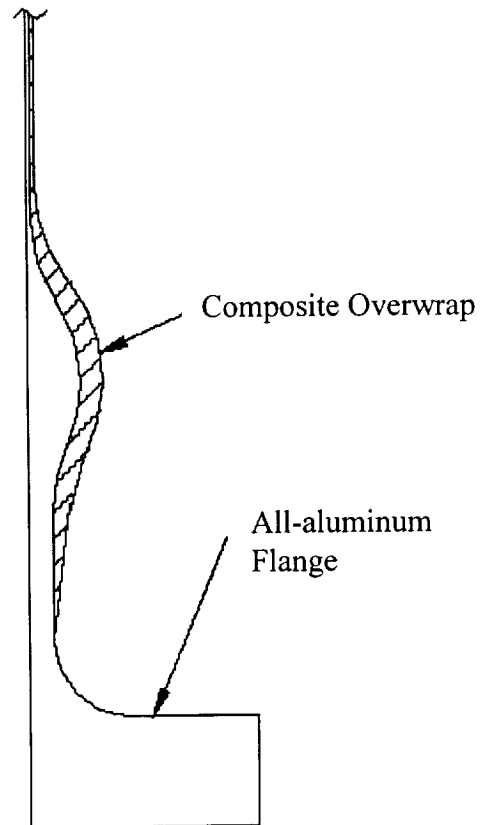


Figure 9 All-aluminum Flange with Composite Overwrap at Center Section only.